Use of permanent magnet quadrupoles in DTL's

The use of permanent magnet quadrupoles in Drift Tube Linacs (DTL) has first been discussed as a option for the Superhilac at LBL[1]. One of the earliest real application of drift tube quads has been build by the New England Nuclear Linac in 1980 [2,3].

Comments about different linacs build or proposed

1.) New England Nuclear Linac 1980

This ~200MHz-machine has been successful commissioned. It was a 45 MeV, 5 mA (225kW beam power) machine with a duty factor of 12%. The injection energy was 780 kV. The Number of drift tubes was 108. The focusing scheme was an FD-structure. After commissioning this linac has been dismantled because of economic reasons.

2.) SSC Linac 1993

The SSC linac has been build by AccSys Technology, Inc. The commissioning of this linac has not been finalized because of the termination of the project. The energy range was 2.5-70 MeV at 428 MHz. The peak current 25 mA at a duty factor of 0.1% The partially completed linac was purchased from Texas by International Isotope, Inc of Denton, Texas.

3.) III (International Isotopes, Inc.)-Linac (Modified SSC linac) – JP Accelerator Works, Inc. (Jim Potter)

Question: "how can you build an accelerator up to 90 MeV without any tuning? I think the basic answer is:
1. make the quads as good as possible,
2. align them properly,
3. do the right matching using a well designed front-end.
Los Alamos people are well aware of this. "

Answer: I agree that it is feasible to do this. The SSC/III quads were almost all within +/- 0.5% with low multipoles - I forget the spec, it was like <0.5% on multipoles and all PMQs we had met it. These quads were carefully assembled and measured by Aster Enterprises. The alignment was to within +/- 0.002 transversely which was half the SSC spec. On the front end we have one PMQ between the RFQ and DTL with no other matching. Between each tank there are 2 PMQ's. They can be moved transversely, one in x, the other in y, to provide a little steering between tanks.

Question: *Are there already build other accelerators using PMQ's?*
Answer: AccSys Technology builds 7 MeV machines using PMQ's. I wouldn't consider building one any other way. I'm surprised that there is a question about this. The SSC application had pretty tight specs on beam quality and the DTL with PMQ's was able to meet their specs.

Question: *What are the data of the DTL you build in Texas.*
Answer: 30 MeV, 40 mA peak, 1 mA average. Hardware for extension to 50 and 70 MeV exists, including all PMQ's, but it hasn't been assembled.

Question: *. what are the magnetic and mechanical data of the SSC quadrupoles*.
Answer: Bore hole was 18 mm, length 1", OD about 2" or 2.5".Gradient min ***?***
Gradient max ***?***

Question:. *Do you have diagnostics in the drift tubes?*
Answer: No. And none were planned for the original SSC application of this linac. The only diagnostics was to be between the tanks, so the design included a 2 beta*lambda space between them, not the normal one beta*lambda.

Question. *What are the tools for the commissioning of the first beam? Can you measure emittance and /or beam size at two different positions behind the linac, while you tune the entrance matching?*
Answer: We (at III) had current transformers, 2 wire scanners, a set of X-Y slits and radiographs of beam on target. This was inadequate diagnostics because we had no way to measure emittances directly. Some crude estimates were obtained by varying the matching quads after the linac and looking at the beam size on the wire scanners.

Question: *Do you optimize for transmission of current.*

Answer: There was no measurable beam loss in the DTL. (I can check with John Kinross-Wright to get you a more definitive statement. I think there is some small loss in Tank I [under 13 Mev] of unknown origin and no detectable loss in Tank 3 [13 – 32.7 MeV]. All of the tuning was done on the beam transport after the linac. This consisted of 4 matching quads and a wide spaced FODO line.
Question: *Do you have some emittance measurements.*
Answer: I do not. There were some estimates made which were much higher than expected, but we don't know the source of the emittance growth or if it was just bad data (or drift tube vibrations – the emittance was good enough for isotope production targets so no effort has been put into resolving it.).

Question: I remember that Berkeley people discussed a *changeable perm. quad* during the construction of the SuperHilac. Maybe Ron can help me with that.
Answer: There were some adjustable PMQ's made for the SSC linac. I don't remember where they were to be used. We didn't use them.
Additional comments:
I don't believe it is feasible to build a 400 MHz DTL without PMQ's.
We installed the quads in order of descending strength. The original spec was for +/-5% tolerance and grading. In practice we found only 5 or 6 outside +/- 0.5%. It would not have been necessary to sort them. Any random arrangement would have worked fine.

4) ACCSYS Linacs being delivered to

Dear Bob, can you put some Information in here about your
Customer, basics magnetic data(Gradient, length, harmonic content), mechanic data(bore, material), Diagnostic for commissioning and operation, Diagnostic inside the tank.
AccSys has built and delivered three short DTL's in addition to the original construction of the SSC DTL completed at III by JPAW. All of our commercial systems use 1 inch long quads with a 1 cm bore at 17.5 kG/cm (±0.35) gradient. We have Aster "tune" them during assembly to have n=3 harmonic below 2.5%, with the total of all harmonics less than 5%. We do not have any diagnostics in the DTL, but use current toroids, and a magnetic spectrometer to measure the energy and energy spread out of the linac. We have used beam spot measurements to measure the emittance on one of our 7 MeV linacs (Hitachi) and the measured normalized transverse emittance (99%) was 0.85 π mm-mrad at 7.0 MeV with a

beam current of 15 mA. IUCF has also made emittance measurements on their AccSys Model PL-7 linac, but I don't have these results.

The three DTL tanks we have delivered are to:
1) BNL - This is the original prototype of our patented design and only goes from 2 to 4 MeV.
2) IUCF - They have the first Model PL-7 linac we delivered, with the DTL going from 3 to 7 MeV. This linac is for accelerating polarized H^- ions.
3) Hitachi - The Model PL-7 linac installed at Tsukuba Medical Center for their proton therapy project was delivered by AccSys in 1998. It accelerates 15 mA of H^+.

The fourth Model PL-7 linac is now being assembled for delivery in November 2000 to ENEA for the TOP project (proton therapy) in Italy.

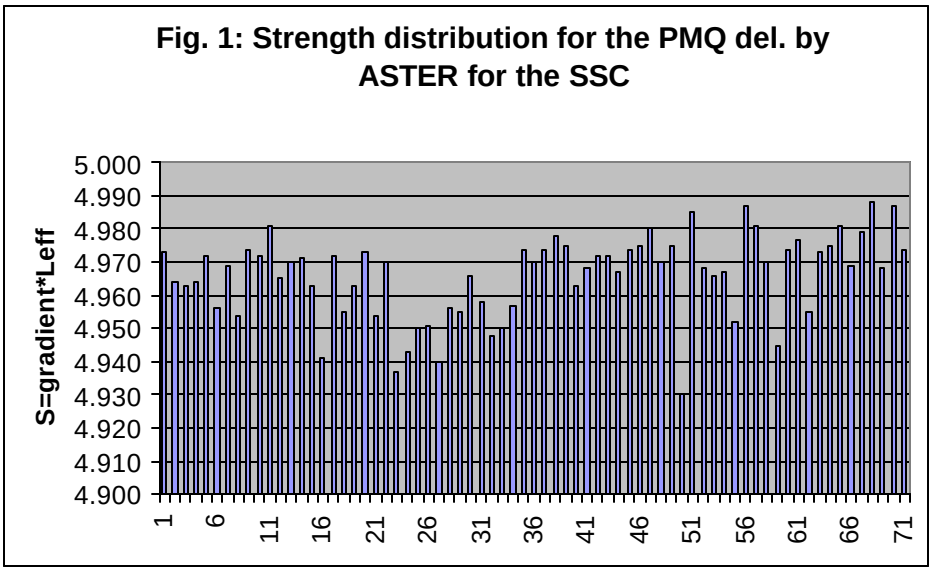
5.) Experience with the 7 MeV IUCF machine – Dennis Friesel

Sig a call to Dennis Friesel: He pointed at the good reliability, the easy turn-on procedure and the fast performed commissioning. The System RFQ+DTL has a transmission of about 85%. This may or may not be related to the usage of PMQ, the losses might occur in the RFQ but not in the DTL.
Dennis pointed out the importance of a very precise alignment between RFQ and DTL.

6.) Evaluation of the PMQ's for the SSC DTL – Ron Holsinger

Figure 1 shows the measured strength data for a set PMQ delivered to LANL by ASTER for the SSC.

Fig. 1: Strength distribution for the PMQ del. by ASTER for the SSC



The deviation from the average value in % is shown in figure 2. The average value is 4.966 T. The distribution after sorting them to ascending strength is shown in figure 3. This might be useful way to place them into the DTL by ascending or descending order.
Furthermore, the Quads could be combined in a way to replace each quad by two quads and combine the most strong with the most weak quad. This combination helps to reduce the errors significant, seen in fig.4. It seems this kind of a sorting procedure could be very helpful to get high precision quadrupoles. But it would double the cost by almost a factor of 2.

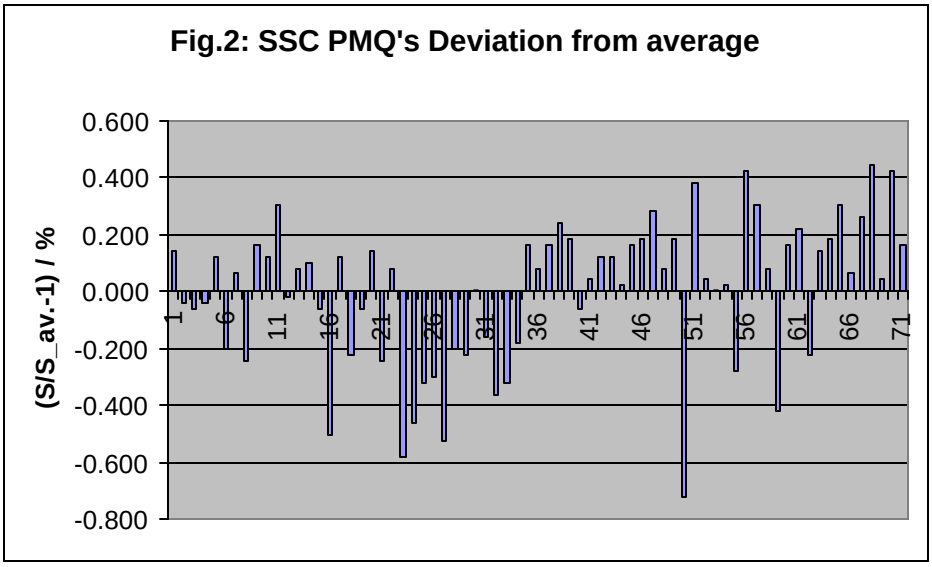


Fig.2: SSC PMQ's Deviation from average
(S/S_av.-1) / %
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.600
-0.800
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71

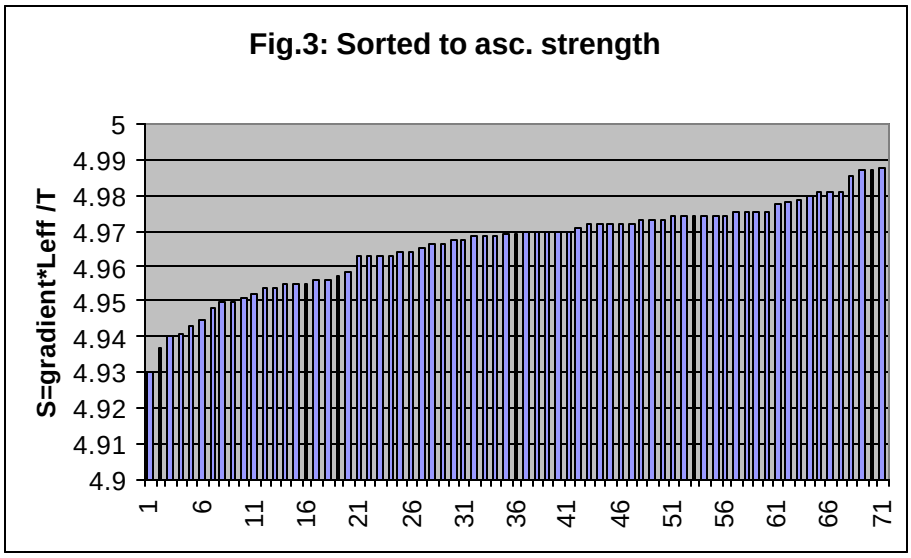


Fig.3: Sorted to asc. strength
S=gradient*Leff /T
5
4.99
4.98
4.97
4.96
4.95
4.94
4.93
4.92
4.91
4.9
1
6
11
16
21
26
31
36
41
46
51
56
61
66
71

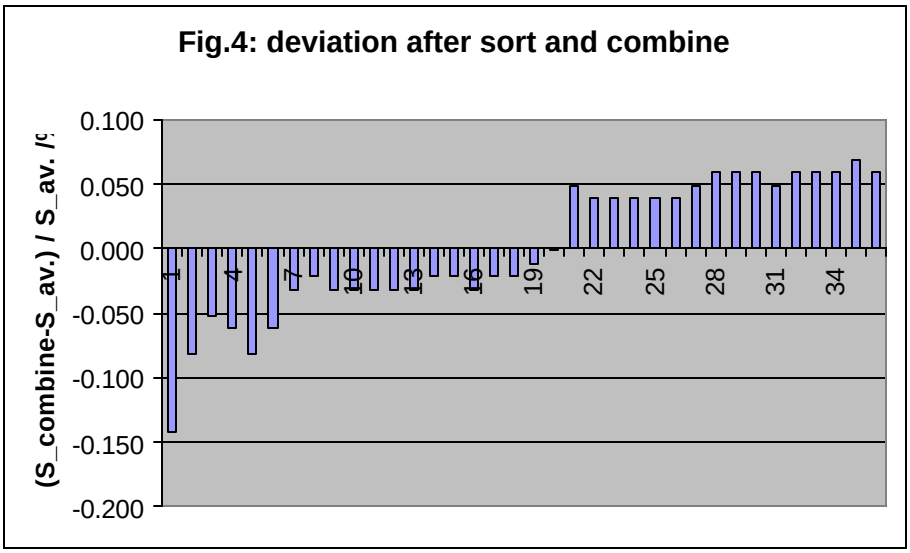


Fig.4: deviation after sort and combine
(S_combine-S_av.) / S_av. /
0.100
0.050
0.000
-0.050
-0.100
-0.150
-0.200
1
4
7
10
13
16
19
22
25
28
31
34

7) The LANL experience – Jim Stovall

"To my knowledge the only DTLs that have used PMQs are the SSC and single tank linacs at Los Alamos.
The SSC linac has been reincarnated at International Isotopes Inc. (III) in Texas and I am very familiar with its problems. Their instrumentation (which was defined by Roy Cutler) is insufficient to detect any mismatch from any source. I am convinced that none of their operational problems stem from their PMQs. Neither could we say that their transverse dynamics is perfect. In other words there is no relevant data here.
We built and operated at least 3 DTLs here during Star Wars where we "perfected" our designs that were then adopted for SSC. These 7 MeV nom. DTLs worked fine but their performance is still classified! It is a big embarrassment to me that we were never able to published our designs or results. I am free to say that their performance was excellent however and for a price the data could probably be found and declassified but not by Sig.
There is one other DTL, built by Bob Hamm, installed at Indiana University……"

References:

[1] K. Halbach, private communication, LBL 1972
[2] R.F. Holsinger, "The Drift Tube and Beam Line Quadrupole Permanent Magnets for the NEN Proton Linac", Proc. 1979 LINAC Conference, Montauk, BNL 51134, and private communication, see section 1.6.
[3] E.A. Knapp, "New Application of Particle Accelerators in Medicine, Materials Science, and Industry", 1981 PAC, IEEE Vol. NS-28, p.3120, 1981